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DISCLAIMER

EVALUATION OF METHOD FOR DYNAMIC IMPACT TESTING OF GYPSUM CONCRETE*

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ABSTRACT

Gypsum concrete plugs are now in use, and light-weight gypsum concrete plugs are being considered for use as part of the stemming materials put in emplacement holes at the Department of Energy's Nevada Test Site. The behavior of these concretes, under dynamic loading, needs to be characterized. This report describes two series of impact tests that were conducted: the first, to evaluate the merits of the test and the measurement method; the second, to evaluate the material properties under dynamic loading.

The method involves dropping a weight from various heights onto instrumented samples. The variation in drop height is done so that the strain rate can be varied from between 30 and 3000 $\mu\varepsilon$/ms (microstrain/millisecond). This is the strain rate range experienced by upper and lower stemming plugs during an event. In the first test series, the samples are confined by either alluvium or gypsum concrete so that confining stresses are varied. This mixing of test geometry was done so that the extent to which strain rate and confining stress can be affected is evaluated. Dynasen ytterbium shock pressure gauges, carbon shock pressure gauges, and concrete strain gauges are used. The major drawbacks with the first method as performed is that the initial states of stress are not known, and not enough variation in dynamic confining stress is achieved. The second series of testing was conducted using only gypsum concrete for confinement. As with the first test series, the strain rates were varied and, thus, the confining stresses were varied. This second series of test had enough variations in strain rate, and thus dynamic confining stresses for an indication of material behavior. Static monitoring of gauges was done before the dynamic testing so that the initial confining stress, due to material expansion during cure, can be identified.

It is believed that the method is proper for determining the strain rate dependency of the material and its relationship to the failure behavior of the material especially in the second series of testing. A comparison with the unconfined static test results indicates that the method allows static failure strains to be met or exceeded. It is felt that the samples tested are large enough, combined with the presence of the sand cover, so that end-effects which are present in the split Hopkinson bar test are not a factor in this test method. The use of longer specimens in most cases necessitates consideration of wave propagation in the specimen. It is felt that the instrumentation geometry gives consideration to this concern. The results of the testing are presented as stress-strain plots from which dynamic moduli for various strains rates are developed. The method also allows for evaluation of strain energy absorption to strain damage. Strain-strain plots are presented, the slope of each is the dynamic Poisson ratio for that strain rate.

INTRODUCTION

The purpose of this study is to evaluate the dynamic impact method used to analyze the strain rate effect on the strength of gypsum concrete. During a Lawrence Livermore National Laboratory (LLNL) contained nuclear detonation test at the Department of Energy's Nevada Test Site (NTS), strain rates of between 30 and 3000 $\mu\epsilon$/ms (microstrain/millisecond) can be experienced by the upper and lower stemming plugs, respectively. Gypsum concrete plugs are being used as part of the stemming material put in emplacement holes at the NTS, and its behavior under dynamic loading needs to be characterized.

The effects of high strain rate or dynamic loading of materials is usually studied in the laboratory by three methods: resonance, pulse propagation, and impact. The first method entails finding the fundamental resonant frequencies of a material specimen, and the second measures the velocities of propagation of pulses in a material specimen. The resonant frequencies or the velocities of propagation are then used to determine the dynamic values of Young's modulus and Poisson's ratio. The drawback to both of these methods is that they are generally limited to small changes of stress. The split Hopkinson bar apparatus is the most common method of evaluating the behavior of materials subjected to dynamic stresses greater than their strength. The drawback of the method is the size of the samples which can be tested. The usual sample size is 1 in. in diameter, which means that the behavior of the specimen can be strongly affected by end-effects and the effects of aggregate size to diameter of the specimen. For most testing an L/D ratio of 2 to 2.5 is maintained. The standard split Hopkinson bar test thus, requires a specimen of 1 in. diameter and 2 to 2.5 in. length. In a concrete specimen containing coarse aggregate, this size is too small to effectively accomodate aggregate greater than one-fifth of an inch, and LLNL coarse fill contains aggregate up to nine-sixteenths of an inch. Because of the problems with aggregate size and end-effects, it was decided that development of a large impact method of testing dynamic strength properties might be useful. Reported here are the results of those large impact tests. From these results a decision will be made as to whether this method of impact testing warrents further development. Major uncertainties (gauge behavior, temperature effects, geometry effects, etc.) exist and, where appropriate, are discussed.

TEST CONFIGURATION

Two series of dynamic impact tests were performed on instrumented gypsum concrete specimens. These tests were conducted at Dyansen, Inc., a commercial instrumentation facility at Goleta, California. The Dynasen drop tower used to perform these tests is shown in Fig. 1. The tower is 30 ft in height but has an effective drop height of only 20 ft. The drop weight can be either 3000 lbs or 5500 lbs. For all of the tests reported here, the larger weight was used. The working cavity into which the instrumented specimens are placed and the weight is dropped has inside dimensions of 24 in. x 24 in. x 18 in. For both series of tests, the specimens tested were of standard concrete cylinder size (6 in. diameter, 12 in. height). Eaton concrete strain gauges were cast in the center of the specimen with one oriented vertically and the other horizontally. A thermistor was placed next to the strain gauges for temperature monitoring during the test. After the specimen of gypsum concrete set, the cylindrical mold was removed and Dynasen stress gauges mounted to the exterior of the specimen. The specimen was covered with a thin coat of epoxy. This epoxy coating cemented the stress gauges in place and retarded drying of the specimens. The water content of the gypsum concrete has been found to have a large effect on the strength of the material. As the water content decreases from drying, an increase in the static compressive strength occurs, corresponding with a more brittle nature.

For all tests, E.G.&G.-Las Vegas was responsible for sample preparation, except stress gauge mounting. The stress gauges were mounted by Dynasen. E.G.&G.-Las Vegas was responsible for all data acquisition during the drop tests.

Test Series I

The Series I tests were conducted in February, 1984 and consisted of six drop tests performed on instrumented gypsum concrete specimens. The specimens tested were mixed and cured at the Dynasen facility using 100 lbs of Cal Seal gypsum cement, 40 lbs of water, and LLNL coarse fill. At the time these tests were conducted, this was the preferred gypsum concrete. Specimen preparation consisted of filling a standard concrete mold with coarse fill and the gypsum cement slurry was added till all voids were filled. The instrumentation of the specimens consisted of a drop hammer stress gauge, 3 vertical specimen stress gauges, 2 horizontal specimen stress gauges, 2 vertical specimen strain gauges, and 2 horizontal specimen strain gauges. This gauge configuration was chosen because at the time E.G.&G.-Las Vegas had a mobile recording facility which could handle only 10 channels of data acquisition.

In this first series of tests, three basic parameters were varied for each test configuration. They were 1) height of fall of drop hammer; 2) number of uninstrumented specimens; and 3) media surrounding the specimens. The parameter configurations are summarized on Table I. The intent of this first series of tests was to vary the dynamic confinement pressure by varying the number of specimens and the surrounding media. By this wide variation of parameters, a feel for the response of the test system was ascertained. Two instrumented specimens were placed in each of the six tests . As indicated by Table I, in Drop Tests 1 and 2 only the two instrumented specimens were present. These specimens were placed along the centerline of the working cavity a minimum of 2 in. apart. The rest of the working cavity was then filled to the specimen height with gypsum concrete in the same manner that the specimens were constructed. After curing, the working cavity full of gypsum concrete, was overlain with 6 in. of NTS desert alluvium. The alluvium was placed as a cushion for spreading out the impact stress pulse. In Drop Tests 3 and 4, two instrumented specimens were placed and the rest of the specimens were uninstrumented. For these tests, one specimen containing two vertical stress gauges was placed at the very center of the working cavity, and a second, partially instrumented specimen was placed diagonally (see Fig. 2) from the center specimen a maximum of 2 in. In all tests the instrumented samples fell within the effective area of the working cavity, as defined by a Dynasen study. This study found that anything lying within 4 in. of the walls of the working cavity would receive up to 97 percent of the impact energy. In Drop Tests 3 thru 4, after placement of the specimens the remainder of the working cavity was filled with NTS desert alluvium (6 in. of alluvium above the top of the specimens).

For these six tests, the hammer drop height was varied to obtain strain rate variations. It was hoped that the variation in confinement and strain rate could be used to characterize failure of the material under dynamic loading. The major drawbacks with the first series of tests is that no measurements were made for evaluating the initial state of stress, no stress gauge strain measurements were made for evaluating strain coupling in the stress gauges, only minimal variation in dynamic confining stress was achieved, and the bottom stress gauges were mounted to the bottom of the working cavity.

Test Series II

The Series II tests were conducted in April, 1985 and consisted of eight drop tests performed on instrumented gypsum concrete specimens. The samples tested were mixed and cured at the Dynasen facility using 100 lbs of W-60 gypsum cement, 100 lbs of Utelite (expanded Shale aggregate), and 50 lbs of water. At the time these tests were conducted, this was the preferred gypsum concrete. Specimen preparation consisted of placing the water and utelite into a ready mixer and agitating for 20 minutes. Agitation was necessary to ensure saturation of the Utelite. After 20 minutes of agitation, the gypsum cement was added to produce the gypsum concrete slurry. This slurry was then poured into standard concrete molds. The instrumentation of the specimens consisted of 4 vertical specimen stress gauges, 4 horizontal specimen stress gauges, 2 vertical specimen strain gauges, 2 horizontal specimen strain gauges, 3 thermisters, and 4 piezoelectric pins. This gauge configuration was chosen so that redundency of all gauges existed. Since the previous test series, E.G.&G.-Las Vegas had increased their mobil recording facility capability so that 36 channels of data could be acquisitioned.

In this series of tests, only one parameter was varied for each test configuration. That was the height of fall of the drop hammer. The tests are summarized on Table II. The intent of this series of tests was to vary the dynamic confinement pressure by varying the height of fall of the drop hammer. In each of the eight tests, two fully instrumented specimens were placed on a 1 in. thick gypsum concrete pad, poured in the bottom of the working cavity. In Drop Tests 1 and 2, a third specimen, instrumented with a gauge developed by the U.S. Army Corps of Engineers at the Waterways Experimental Station (WES) in Vicksburg, Mississippi, was also placed. The two fully instrumented specimens were placed along the centerline of the working cavity a minimum of 1 in. apart. The third specimen was placed diagonally between the two specimens (see Fig. 2) a minimum of 1 in. from the adjacent specimens. In all tests the main instrumented samples fell within the effective area of the working cavity, as defined by a Dynasen study. After the specimens were placed, the working cavity was filled to a height of 1 in. above the specimens with gypsum concrete slurry in the same manner that the specimens were constructed. After curing, the gypsum concrete was overlain with 3 in. of dry, well-graded fine sand to spread out the stress pulse. During the curing of the gypsum concrete in the working cavity, all gauges were monitored so that the temperature effects on the gauges could be corrected, thus, allowing for definition of the initial state of stress. It was hoped that, with the definition of the initial state of stress and the variation of only one test configuration (strain rate), the dynamic nature of the material could be characterized. Drawbacks exist which make this difficult. One major drawback is the apparent failure of the fluid coupled stress gauges. All of the vertical mounted gauges, for horizontal stress measurements, indicated strains which are not correctable. Strain correction of stress led to its negation. Another is the unknown temperature effects on the Dynasen stress gauge.

DROP TEST RESULTS

The intent of these tests was to come to some conclusion about the dynamic strength of the gypsum concrete and to evaluate whether this method of impact testing warranted further development. The dynamic strength of a material is defined generally by the dynamic Young's modulus and Poisson's ratio. The values for the dynamic strength parameters are usually greater than the static values. With increasing confinement, materials have a tendency to become stronger and more ductile. It was evidence of this extreme ductile behavior in the tunnels at NTS that initiated the concern about dynamic behavior of the gypsum concrete in contained nuclear detonations.

The most common method of evaluating the strength of a material is by triaxial compression testing of a cylindrical specimen whose length is two to three times its diameter. The axial and lateral strains are measured along with the force applied to the top of the sample so that a stress-strain curve can be generated. It is the slope of the straight line portion of this stress-strain curve which gives the material property parameter known as the elastic or Young's modulus. A ductile material is one which can undergo plastic deformation without losing its ability to resist loads. It is the point of transition from elastic behavior to ductile behavior that is known as the yield point. For complete characterization of a material, the Poisson's ratio parameter is also needed. The slope of the initial straight line portion of the lateral strain-axial strain curve is the Poisson's ratio of the material. The lateral strain-axial strain curve can also be used to identify the yield point. The slope of the lateral strain-axial strain curve changes with the onset of ductile behavior.

The effects of confining pressure on strength and ductility can be further characterized by establishing a criterion of failure. For this to be done the effects of confinement on the material need to be established, along with the mode of failure and the strain energy capacity of the material. Endochronic Theory is a constitutive model used to characterize the accumulation of inelastic strains in portland concretes. The hysteretic behavior evidenced in these tests indicates that Endochronic Theory may be a valid model for gypsum concrete. The theory is mentioned as a possible direction of study in the future if very general material parameter studies do not provide an adequate modeling of the dynamic properties of gypsum concrete.

Test Series I

From the Series I Drop Test results, indications are that the maximum drop height corresponds with strain rates expected in a lower stemming plug. The lowest drop height used gives strain rates higher than that expected in an upper stemming plug. A factor of ten difference in strain rates between the high and low drop height is felt to be adequate for determination of any strain rate effects on strength. It is considered reasonable to assume that greater dynamic confining stresses will be generated with increasing drop height. This dynamic stress is in addition to the static confining stress developed during the curing of the gypsum concrete in the working cavity. It is speculated that the initial confining stress is somewhere between a hoop stress, developed by expansion of the material, and an overburden factor stress. The magnitude of the dynamic component of the confining stress is not known. The coupling of the strain in the gauges along with the coupling of the vertical and horizontal stress gauges makes all magnitudes of stress obtained suspect. The stress gauges used in this series of tests were either Dynasen ytterbium or carbon shock pressure gauges. There is no such thing as a stress gauge, just a strain gauge whose element has been calibrated for stress conversion. The calibration factor usually takes Poisson's effect of the gauge element into consideration.

From the data collected, stress-strain and strain-strain curves are developed. Examples of these curves are shown in Figs. 3 and 4. From these curves the engineering material parameters are determined. These parameters are listed in Table III. As can be seen the values are inconsistent. No pattern of modulus to strain rate can be seen. Figure 5 presents the Young's modulus versus strain rate data along with a least-squares regression analysis of the data. This regression analysis is presented only as an exercise, and does not represent the relationship of dynamic Young's modulus to strain rate. Even though a regression analysis was done, it is felt that the Young's moduli calculated varied too much for a conclusion to be drawn. As suggested previously, this is assumed to be due to the problems of strain coupling in the gauges. This coupling should cause the gauges to yield higher stresses than are present. This in turn should yield higher moduli. The data doesn't bear this theory out, but strain gauge uncertainties exist which may have cancelled out this stress gauge effect. The strain values need to be corrected for thermal expansion differences between the portland concrete, the strain gauges were designed for, and the gypsum concrete. No temperature measurements were taken for this correction to be made. These gauge uncertainties coupled with the changes in test configuration are felt to make any conclusion of strain rate effects on Young's modulus of the material unwarranted.

The Poisson's ratio of straight gypsum cement is given in materials handbooks to be .24. It is reported that this poisson ratio is independent of initial water content. This indicates that this is the Poisson's ratio of completely air-dried gypsum cement. It was expected that the dynamic Poisson's ratio would be smaller than is found in triaxial testing because most of the strain would be occuring vertically, with much smaller horizontal strain adjustment to the dynamic loading. Most of the data bore this out.

Test Series II

From the information gathered in the first series of tests, a second series of tests was planned. The second series of tests was designed using Dynasen ytterbium fluid coupled shock pressure gauges so that the problems with strain coupling could be corrected. Redundency of gauges was called for as this would provide a better statistical basis for developing the average stress. All tests were configured the same with only the drop height changed. Drop heights were repeated so that the same general strain rate would be tested twice.

All gauges were monitored during the curing process so that an initial state of stress could be determined. It was during this monitoring that problems with the horizontal stress gauges were noted. These gauges developed strains, during the curing of the gypsum concrete, indicating that the fluid coupling was not working. None of the vertical stress gauges developed strains. In all but Drop Test 2 and 5, residual strains were measured in the horizontal stress gauges after dynamic testing. A comparison to the Eaton strain gauge data indicated that appreciable permanent horizontal strains were present only in Drop Test 1 and 8. The magnitude of the strains, measured in the horizontal stress gauges, was so great that correction of the stresses was not reasonable. In Drop Test 2 and 5 the working cavity leaked. This resulted in a reduced water content in the gypsum concrete surrounding the instrumented samples. It was noted that the stress gauges in these two tests did not develop the residual strains after dynamic testing. It is speculated that the hydrostatic pressure developed during the curing may affect the gauge.

It was also noted that the gauges were designed for perpendicular orientation to the shock pulse. It was speculated that the planer propagation of the wave on the gauge could affect measurements. This theory was tested with a gas gun experiment. The results indicated that planar wave propagation does not affect the gauges ability to measure stress. The planer wave generates high shear stresses in the fluid reservoir which affects the strain in the gauge element.

The horizontal stress gauge measurement taken during curing, indicates development of an average confining stress of 4550 psi. The static strain measurements taken, combined with a static Young's modulus of $1.5x10^6$ psi, and a Poisson's ratio of .30 give an average initial confining stress of 1480 psi. This value is a factor of 3 lower than the stress indicated by the horizontal stress gauges. This difference is probably due to the failure of the fluid coupling in the gauges. The failure of the horizontal stress gauges makes evaluation of the dynamic confining stress generated impractical.

The vertical stress gauges developed no appreciable strains during curing. In Drop Test 1 and 2, a WES gauge was placed in the center of a third specimen. In Drop Test 1, the WES gauge measured a peak vertical stress of 5000 psi. This gives a percent difference of 1.2% from the Dyansen gauge. In Drop Test 2, the WES gauge measured a peak vertical stress of 1430 psi. This gives a percent difference of 31% from the Dynasen gauge. This large difference may be due to a reduction in effective impact to this specimen. The effective impact area is defined at full drop height, it is thought that the effective area of impact decreases with decreasing drop height. Since the problem of strain coupling was resolved in the vertical stress gauges, the measured peak vertical stress is not as high as that measured in the first series of drop tests.

Stress-strain curves were developed even though no confining stresses were available for comparison. The relationship of Young's modulus to increased confinement is implied because the various strain rates were developed by varying the drop height and thus the dynamic confining stresses. The stress-strain curves generated indicate that Drop Test 1, 2, 6, and 8 exceeded the yield limit of the material and plastic deformation occurred. The peak vertical stress values reported are approximately the dynamic yield strengths for the material at those strain rates. Unfortunately, dynamic confining stresses are needed before the material can be adequately characterized. No evidence of failure of the material was seen during any of the test dismantling. A comparison with the unconfined static test results indicates that Drop Test 1, 2, 3, 6, and 8 exceeded the static unconfined strength (1850 psi) of the gypsum concrete.

Strain-strain curves could not be developed for all the tests due to failure of some of the horizontal strain gauges. The strain gauges used in this series had one-eighth inch cables compared to three-eighths inch cables in the Series I tests. This smaller cable was very delicate and did not survive specimen preparation about half of the time. In this second series of tests, temperature was monitored. The strains were temperature compensated and the strain values corrected for the difference in thermal expansion of the gypsum concrete to that of the gauge. The gauge had a thermal expansion of 6.0 ppm/^{o}F. Gypsum cement with Utelite has an average thermal expansion of 4.1 ppm/^{o}F. Strain-strain curves generated from the data available, like the first test series, mainly yielded Poisson's ratios below the static value. An example of the curves generated for this series of tests are shown in Figs. 6 and 7.

The dynamic parameters found are listed in Table IV. This test series resulted in much more consistent modulus values. These values are plotted on Fig. 5. A least-squares regression analysis of the data indicates only a slight increase in the Young's modulus with increasing strain rate. Again, this analysis was done mainly as an exercise, the data base is not felt to be adequate enough to warrant a conclusion on the strain rate effect to dynamic Young's modulus. Samples were taken of all mixes and tested in static unconfined compression. The results of these tests indicate that a wide variation of static Young's modulus and compressive strength can be obtained. The static Young's modulus varied from 1.10×10^6 to 1.60×10^6 psi. The compressive strength varied from about 1200 psi to 2000 psi. This variation in static test results seems comparable with that obtained in the dynamic tests.

No useful results were obtained from the piezoelectric pins placed in the samples. It was hoped that these could be used to time the travel of the stress pulse. This would have provided another means of evaluating the dynamic Young's modulus. The pins did not have a fixed response to the stress pulse, thus timing difference between pulse arrivals could not be ascertained. The pins were also very sensitive to water. Even with epoxy protection of the connections, shorting of the pins occurred in most of the tests.

CONCLUSION

It is believed that the method is proper for determining the strain rate dependency of a material. The method allows for excedence of the unconfined static failure stresses and strains. With modifications to either the impact hammer or the size of the specimen in the working cavity, higher peak vertical stresses can be obtained. This would allow for more characterization of the plastic behavior of the gypsum concrete under dynamic loading. The second series of tests showed that vertical stress-strain curves could be developed from which the dynamic Young's modulus could be obtained. The stress-strain curves indicated that the elastic limit of the material had been exceeded. With development of a valid stress measurement system it is felt that the dynamic yield strengths obtained can be related to a level of dynamic confinement.

With further development it is envisioned that the increase in dynamic yield strength of a material can be evaluated against either increasing dynamic confinement, or strain rate. The effects on horizontal or radial strain can also be developed for increasing confinement or strain rate. With development of an adequate stress measurement system, the deviatoric stress-strain relationship of the material can be developed, along with the strain energy capacity of the material.

Because of costs, this method will never replace the split Hopkinson bar test, but has a place in the field of containment engineering where the dynamic properties of the material are of critical importance. Further development of this method would provide a means of testing more definitively the dynamic behavior of the material of concern, especially if that material is not compatible to split Hopkinson bar testing.

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TABLE I. Summary of Series I Drop Test Results.

Drop Test	Maximum Average Vertical Stress (psi) #	Maximum Average Horiz. Stress (psi) #	Maximum Average Vertical Strain (με) ##	Maximum Average Horiz. Strain (με) ##	Vertical Strain Rate (με/ms)	Number of Test Specimens	Drop Height (ft)	Media Around Specimens	Condition of Specimens After Test
1	7610	3190*	7100	200	3500	2	18	Gypsum Concrete	no visible damage
2	3480	2045*	2400	350	1000	2	7	Gypsum Concrete	no visible damage
3+	3920	800	62500	37000	22200	12	7	Dry Alluvium	center 1/3 rubble
4	6380	2500	9520	3290	3380	11	7	Wet Alluvium	slight damage
5	4350	2420	1760	85	500	5	3	Wet Alluvium	no visible damage
6++	3000	2175	3750	680	1000	12	7	Wet Alluvium	no visible damage

NOTES:
- # Measurements are not corrected for strain coupling of gauge.
- ## Measurements are not corrected for thermal expansion difference.
- * Probable coupling of gage with vertical stress component.
- + Lost gages; results are questionable.
- ++ Samples were only 6" in height.

TABLE II. Summary of Series II Drop Test Results.

Drop Test	Maximum Average Vertical Stress (psi)	Maximum Average Horiz. Stress (psi) *	Maximum Average Vertical Strain (με)	Maximum Average Horiz. Strain (με)	Vertical Strain Rate (με/ms)	Number of Test Specimens	Drop Height (ft)	Media Around Specimens	Condition of Specimens After Test
1	4940	400	4010	270	2400	3	18	Gypsum Concrete	no visible damage
2	2070	870	3280	---@	2140	3	13	Gypsum Concrete	no visible damage
3	2090	550	2000	150	1280	3	8	Gypsum Concrete	no visible damage
4	1250	600	850	40	400	3	3	Gypsum Concrete	no visible damage
5	1140	830	700	---@	440	2	3	Gypsum Concrete	no visible damage
6	2310	2180	1350	---@	790	2	8	Gypsum Concrete	no visible damage
7+	1750	1210	670	220	300	2	13	Gypsum Concrete	no visible damage
8	4440	4690	4250	140	3800	2	18	Gypsum Concrete	no visible damage

NOTES:
+ Drop hammer jumped tracks, didn't impact sample squarely.
* Measurements not corrected for strain coupling.
@ Lost all both horizontal strain gauges.

TABLE III. Engineering Properties from Series I Drop Test Results.

Drop Test	E_s (psi) *	ν_{sl} +	ν_{su} ++
1	1.21×10^6	0.07	0.10
2	1.51×10^6	0.14	0.16
3	0.10×10^6	0.60	——
4	0.72×10^6	0.37	0.23
5	2.22×10^6	0.07	0.04
6	0.79×10^6	0.17	0.15

NOTES: * Secant Modulus of Stress-Strain Curves.
+ Secant of load portion of Strain-Strain Curve.
++ Secant of unload portion of Strain-Strain Curve.

TABLE IV. Engineering Properties from Series II Drop Test Results.

Drop Test	E_s (psi) *	ν_{sl} +	ν_{su} ++
1	1.94×10^6	0.42	0.38
2	1.39×10^6	----#	----#
3	1.40×10^6	0.04	0.02
4	1.16×10^6	0.11	0.08
5	0.79×10^6	----#	----#
6	1.20×10^6	----#	----#
7	1.40×10^6	0.32	0.22
8	0.87×10^6	0.05	0.05

NOTES:
- * Secant Modulus of Stress-Strain Curves.
- \+ Secant of load portion of Strain-Strain Curve.
- ++ Secant of unload portion of Strain-Strain Curve.
- @ Drop hammer jumped tracks, poor impact.
- \# Lost both horizontal strain gauges.

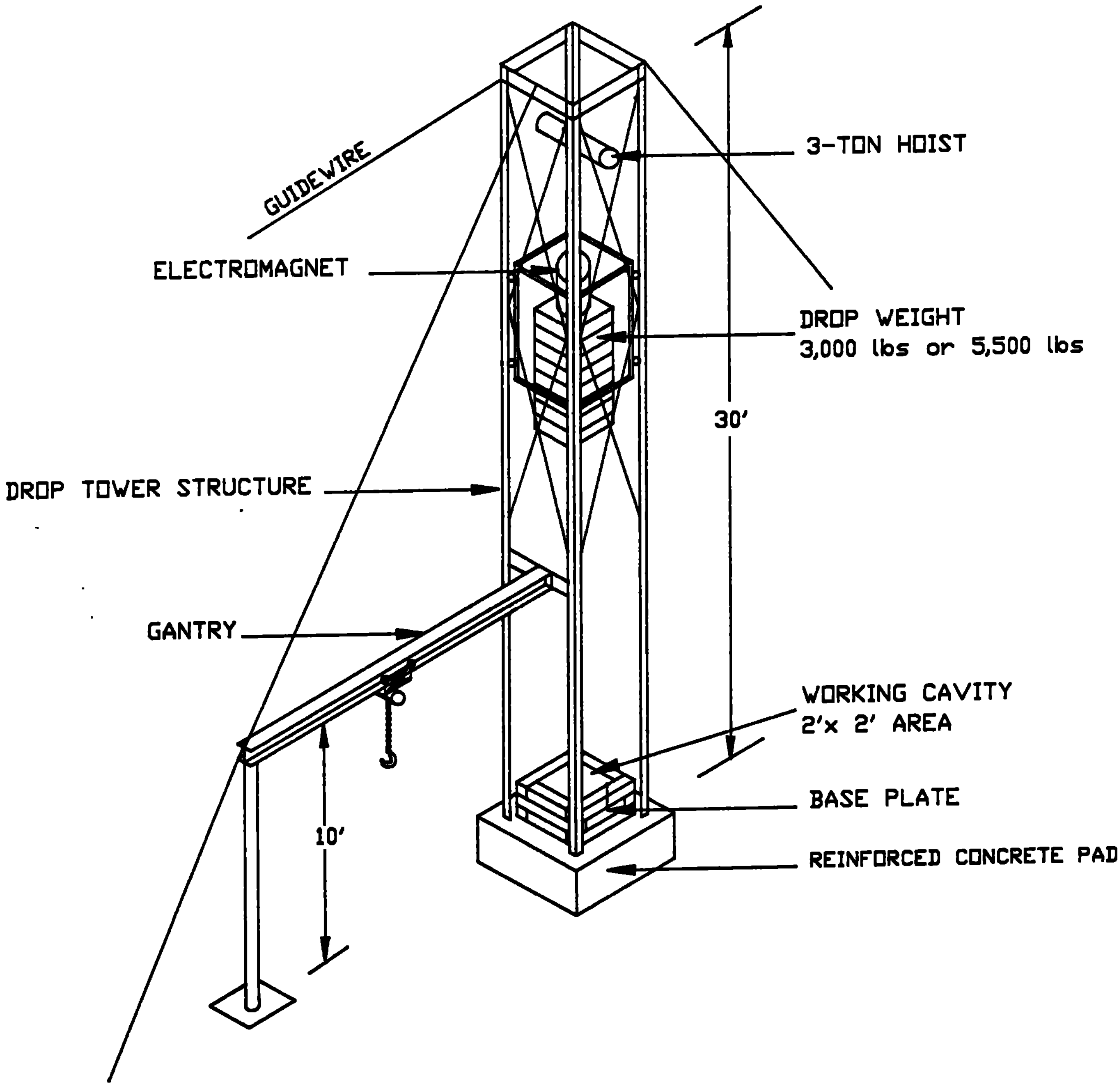
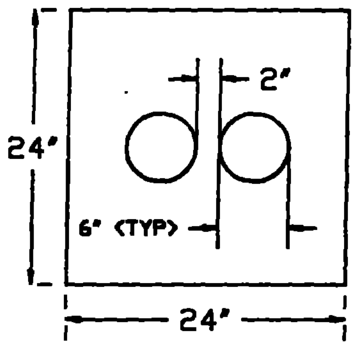
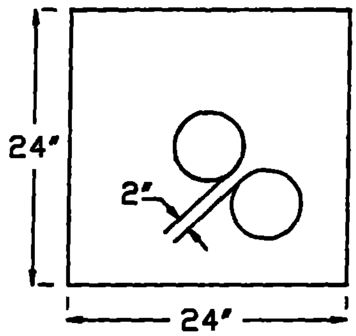


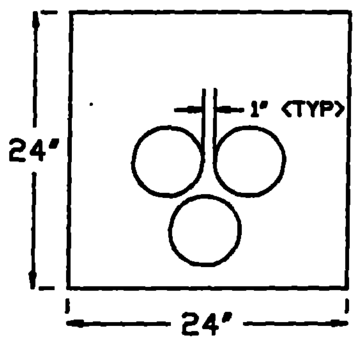
FIGURE 1. DYNASEN DROP TESTER FACILITY



A. DROP TEST 1 AND 2 OF SERIES I TESTS AND
DROP TEST 5 THRU 8 OF SERIES II TESTS (W/1" SPACING)



B. DROP TEST 3 THRU 6 OF SERIES I TESTS



C. DROP TEST 1 THRU 4 OF SERIES II TESTS

FIGURE 2. CONFIGURATIONS FOR MAIN SPECIMEN PLACEMENT IN THE WORKING CAVITY FOR SERIES I AND II DROP TESTS

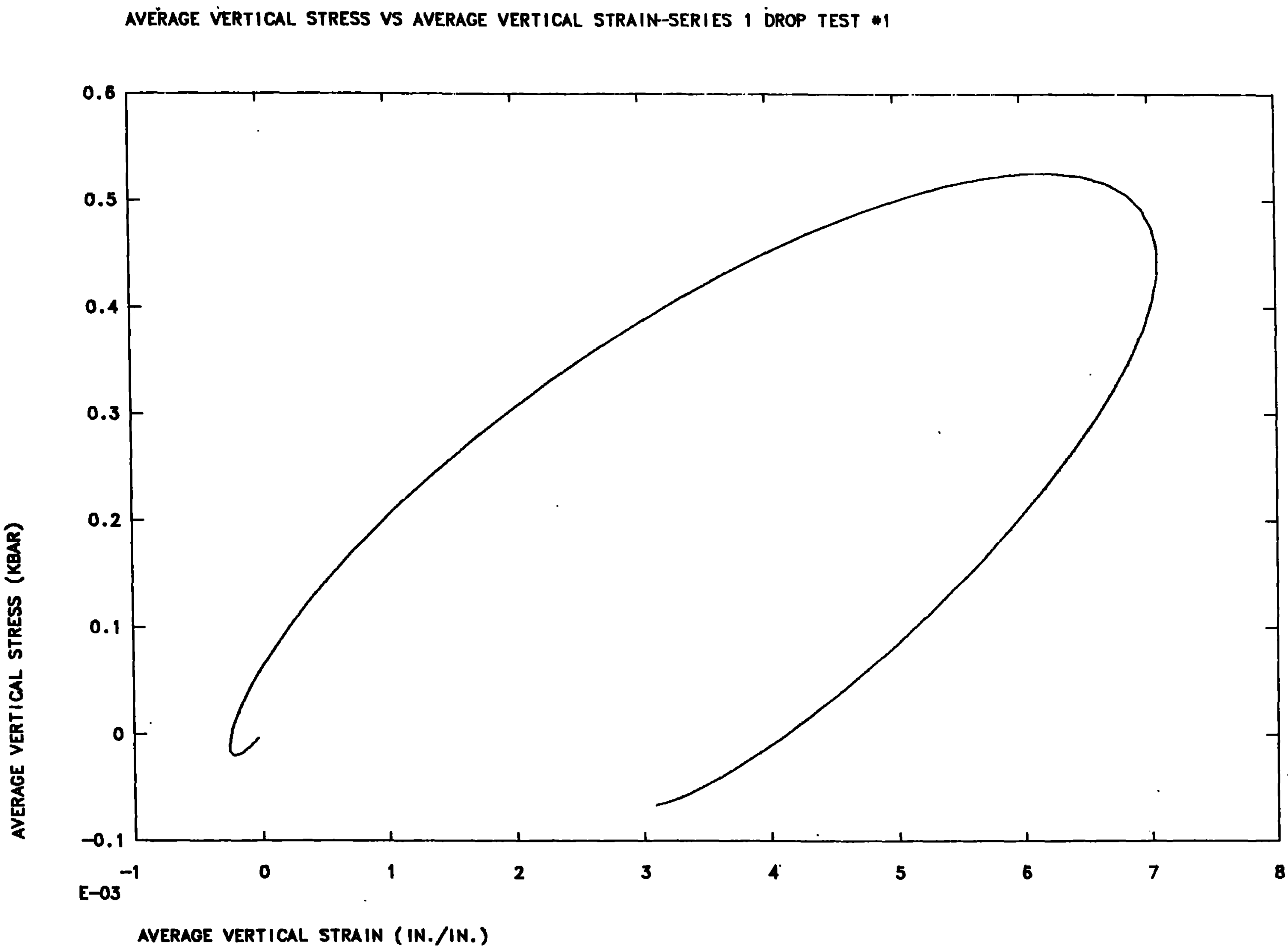


Figure 3. Average Vertical Stress versus Average Vertical Strain - Series I Tests

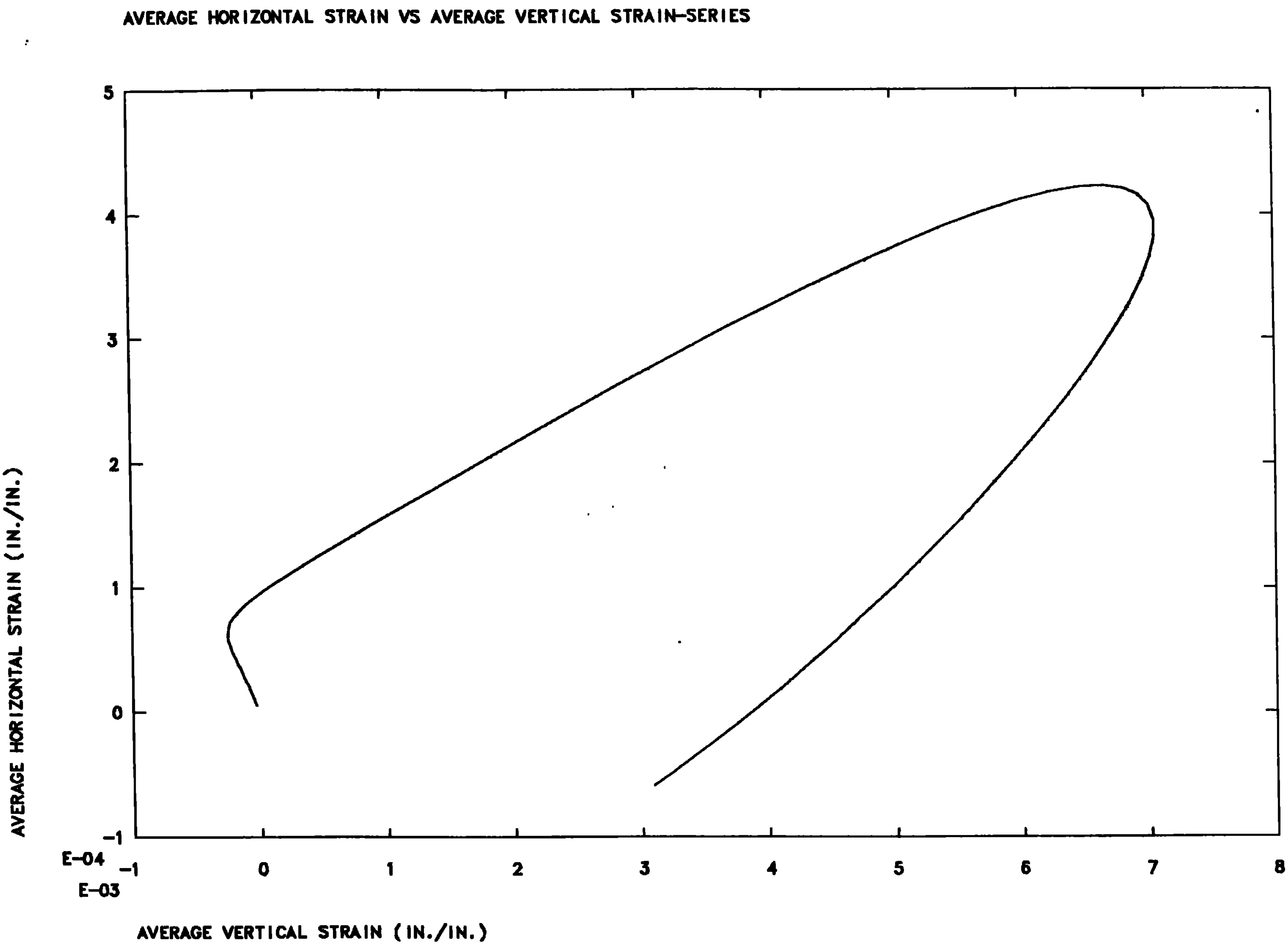
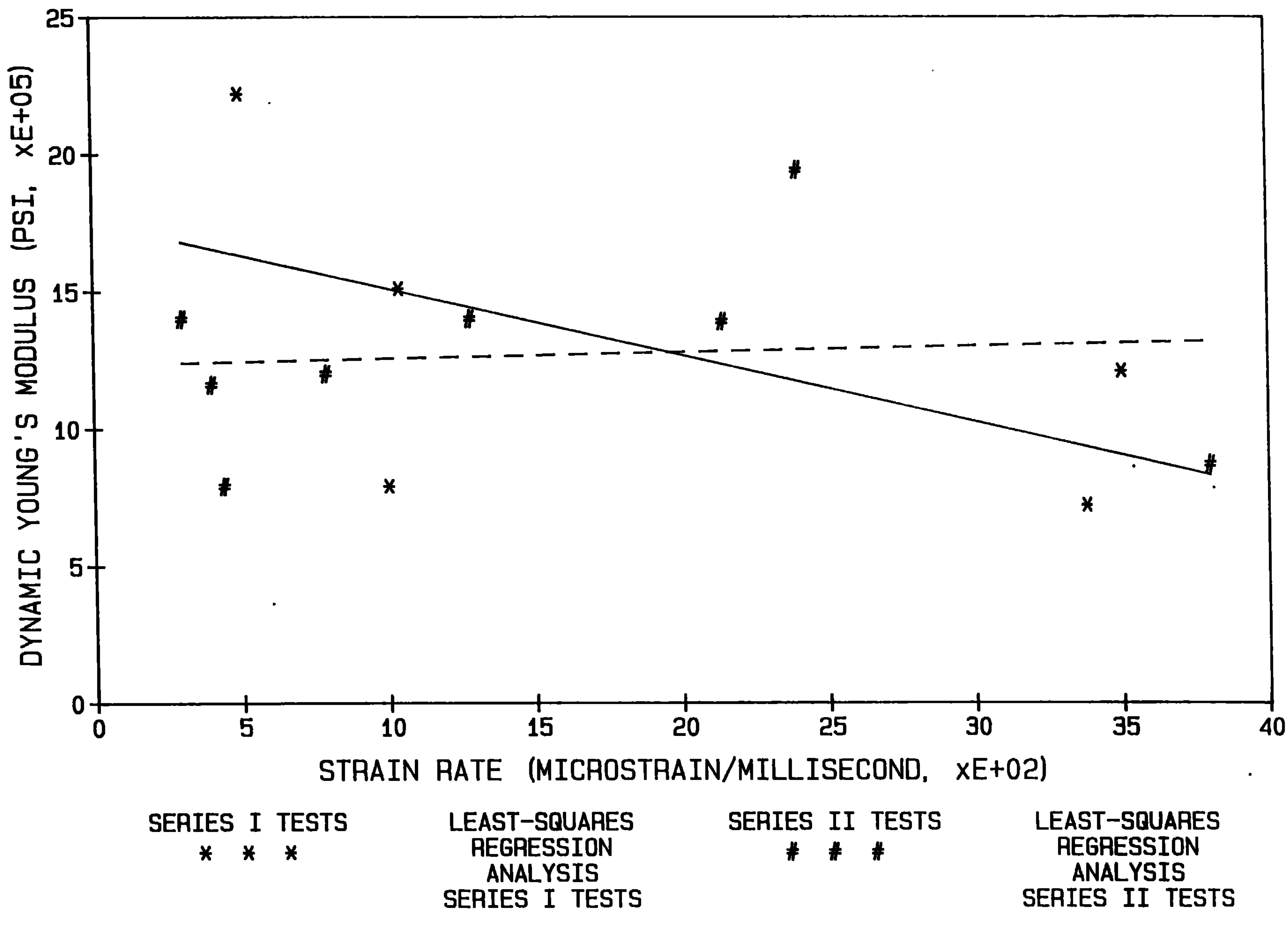


Figure 4. Average Horizontal Strain versus Average Vertical Strain - Series I Tests

FIUGURE 5. MODULUS PARAMETER VALUES FOR SERIES I & II TESTS



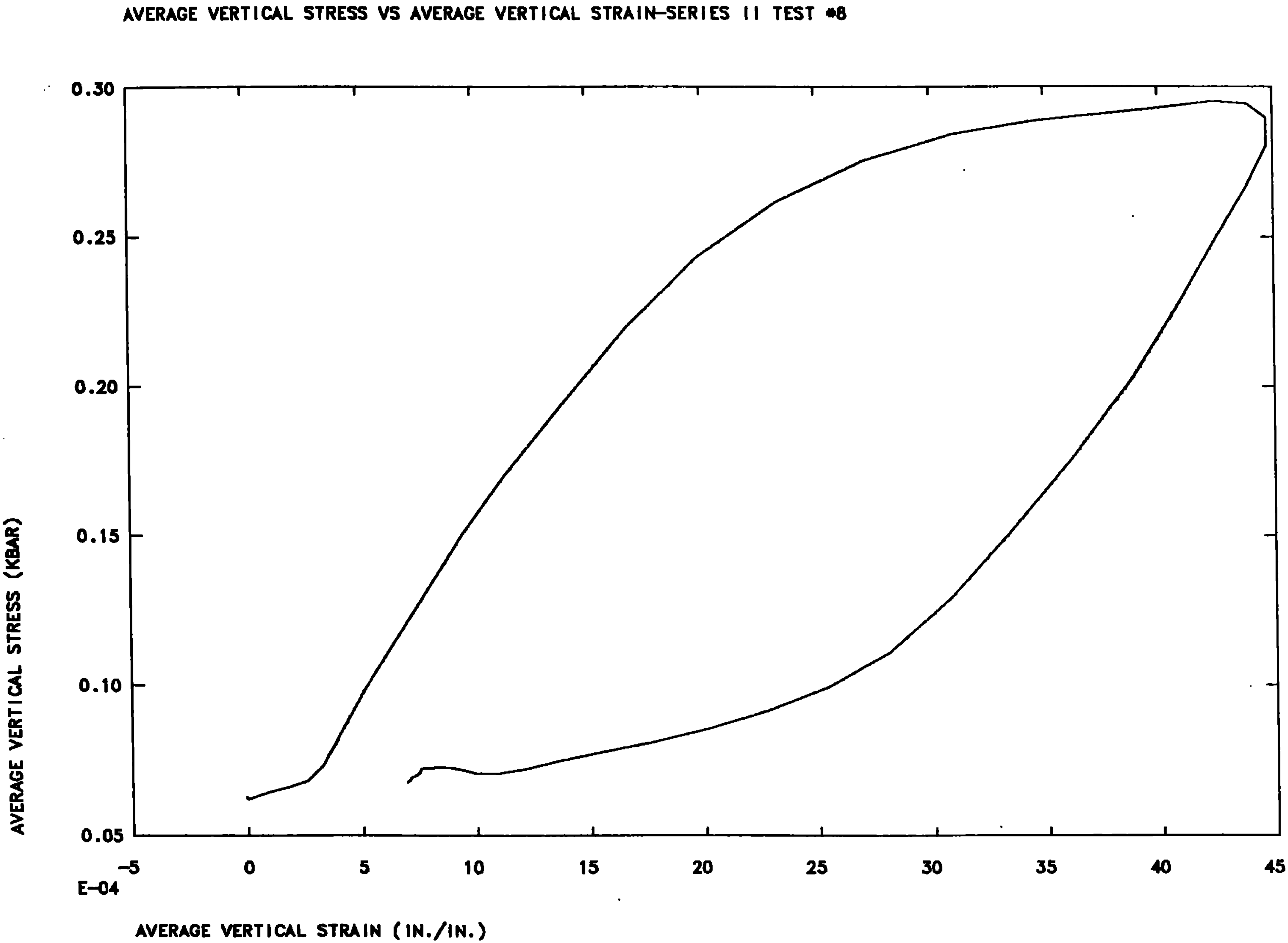


Figure 6. Average Vertical Stress versus Average Vertical Strain - Series II Tests

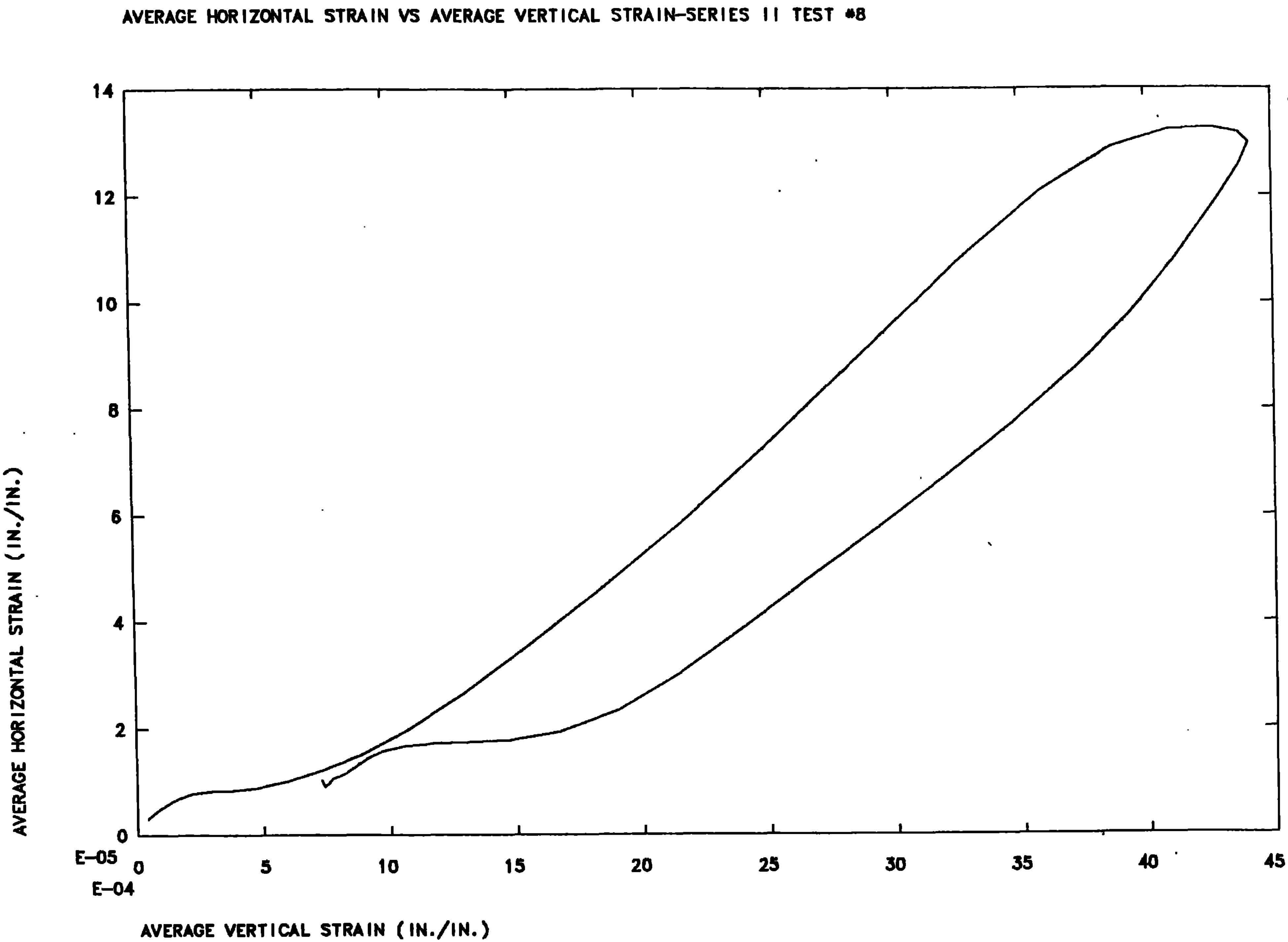


Figure 7. Average Horizontal Strain versus Average Vertical Strain - Series II Tests